Solid Oxide Fuel Cell Auxiliary Power Units for Long-Haul Trucks

Modeling and Control

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Operated by Battelle for the U.S. Department of Energy

Project Objectives

- Develop dynamic model of APU system including SOFC, diesel POX reformer, power conversion electronics and electrical hotel loads.
- Design a system controller to minimize diesel fuel consumption while satisfying electrical load requirements.
- Investigate different system configurations and their impact on overall efficiency.
- Determine the dynamic response of an APU systems to the vibration environment characteristic of a Class VIII truck.
- Develop a structural finite element model to determine dynamic stresses for a planar SOFC stack in the APU.
- Define vibrational limits for SOFC materials based on dynamic stresses and appropriate failure criteria.

Project Description

Long-haul trucks require electrical power to operate lights, heating/air conditioning and televisions while parked for the operator to rest. These loads are often referred to as hotel loads, since the truck cab serves as a hotel room for the driver. Auxiliary Power Units (APU) based on diesel generators are used to provide this power, rather than idling the engine, because they use less fuel and reduce wear and maintenance of the truck engine. While still in the research phase, Solid Oxide Fuel Cell (SOFC) based APUs hold the promise of greater energy efficiency, lower operating costs, lower emissions, and quiet operation. The SOFC APU Modeling and Control program at the Pacific Northwest National Laboratory (PNNL) has two primary goals: 1) develop control systems to utilize the APU efficiently for typical truck hotel loads and 2) develop a dynamic structural model to assess APU durability for the vibrational environment characteristic of large trucks.

Relevance

- Demonstrates component and system durability (FreedomCAR objective).
- Tool to minimize SOFC weight (FreedomCAR goal of 50% weight reduction for vehicle structure and subsystems).
- Improved modeling and control will increase efficiency and reduce costs (FreedomCAR goal of 45% efficiency in reformer based fuel cells).
- SOFC based truck APU will reduce long haul truck fuel usage and dependence on foreign oil (FreedomCAR objective).
- Tool for improving start-up time and reducing sulfur content in APU reformates (HFC&IT goals).

Accomplishments to Date

- Creation of APU System model in MATLAB.
- Electro-chemical and thermal model of SOFC during heat-up and operation phases.
- Dynamic model of truck HVAC system, including inrush current at startup and heat source of driver.
- Controller to regulate cathode air temperature during heat-up phase to prevent thermal shock and stress of SOFC stack.
- Creation of lumped parameter model in ANSYS to determine influence of APU components on stack dynamic response.
- Creation of detailed finite element model of SOFC stack to determine resonant frequencies and dynamic stresses due to harmonic excitation.

Project Timeline

Task	%	Start	Finish
Numerical Modeling			
System Controls Modeling	**3**	**1-Oct-02**	**30-Sep-05**
System Configuration and Connectivity Options	100	15-Dec-02	30-Jan-03
Develop Dynamic SOFC Model	90	1-Jan-03	31-May-03
Develop Dynamic Balance of Plant Model	60	1-Feb-03	15-Jun-03
Complete System Dynamic Models		15-Jun-03	15-Jun-03
Examine Dynamic Performance	5	1-May-03	15-Aug-03
Evaluate Dyanmic Performance During Start-up		15-Aug-03	15-Aug-03
Determine Control Variables	100	1-Jan-03	30-Jan-03
Determine Dependences of Variables	50	1-Feb-03	30-Jun-03
Design and Test Controller	10	15-Apr-03	15-Sep-03
Initial System Controller Complete		15-Sep-03	15-Sep-03
Incorporate Sulfur into Model		1-Oct-03	1-Feb-04
Collect Empirical Data from SOFC and POX		1-Jan-04	1-Jun-04
Develop System ID Models for Internal Variables		1-Feb-04	1-Jul-04
Improved System Model		1-Jul-04	1-Jul-04
Refine Controller to Increase Efficiency		1-May-04	1-Aug-04
Connectivity Options to Increase Efficiency		1-May-04	1-Aug-04
Increased System Efficiency		1-Aug-04	1-Aug-04
Design and source controller and APU hardware		1-Aug-04	15-Sep-04
Preliminary Design for APU Hardware		15-Sep-04	15-Sep-04
Implement Controller on Real APU		1-Oct-04	30-Sep-05
Functioning APU with Control		30-Sep-05	30-Sep-05
Structural Modeling	**3**	**1-Oct-02**	**30-Sep-05**
Material Property Definition	80	1-Dec-02	30-Jan-03
Dynamic Excitation Definition	80	1-Jan-03	30-Jan-03
Lumped Parameter Model	70	1-Jan-03	30-Apr-03
Finite Element Stack Model	60	1-Feb-03	30-May-03
Vibration Models & Methods Complete		30-May-03	30-May-03
Failure Modeling	5	1-May-03	1-Aug-03
Parametric Analysis	0	1-Jul-03	1-Sep-03
FY03 Analysis Completed		1-Sep-03	1-Sep-03
Modeling Support for Seal Testing		1-Oct-03	1-May-04
Modeling Support for PEN Testing		1-Oct-03	1-May-04
Lifetime Durability Modeling		1-Nov-04	1-Jul-05
Data Gathering			
Truck Experimental Data Collection		**1-Oct-03**	**30-Sep-04**
Identify Industry Collaborator		1-Jan-04	1-Jan-04
Determine APU mount locations		1-Mar-04	1-Apr-04
Define Test Conditions and Procedure		1-Mar-04	1-May-04
Gather Vibration Data		1-May-04	30-Jul-04
Log Data of Real Truck APU Usage		1-Jan-04	1-Apr-04
Component Dynamic Testing			
Seal and PEN Durability Testing		**1-Oct-03**	**30-Sep-04**
Define Geometry, Test Matrix and Procedure		1-Oct-03	30-Dec-03
Room Temperature Dynamic Testing		1-Jan-04	1-May-04
Elevated Temperature Dynamic Testing		1-Mar-04	1-Aug-04
Forensic Examination of Failure		1-Feb-04	30-Jul-04
Mock-Up Durability Testing		**1-Oct-04**	**30-Sep-05**
Define Representative Cell Geometry		1-Oct-04	30-Dec-04
Determine Method to Leak Check Geometry		1-Nov-04	1-Feb-05
Generate Test Matrix, Procedure, and Specimen		1-Nov-04	1-Mar-05
Room Temperature Dynamic Testing		1-Feb-05	1-Jul-05
Elevated Temperature Dynamic Testing		1-Apr-05	1-Aug-05
Forensic Examination of Failure		1-Mar-05	1-Sep-05
Testing Completed for Mockup		1-Sep-05	1-Sep-05

Collaborations

Georgia Tech : Failure modeling.

U. of Illinois at Chicago : Electrical system modeling.

Delphi : APU modeling and controls.

PACCAR : Real world data and relevancy.

Lumped Parameter Model

Simplified model to analyze vibration amplitude of planar SOFC stack due to base excitation of an APU system.

Approach

- Represent components as single degree-of-freedom (SDOF) oscillators with generalized mass and stiffness parameters using the assumed-modes method and Hamilton's Principle.
- Perform sine sweep over the frequency range of interest with appropriate base excitation and obtain stack loading history.

Results

- APU model implemented in ANSYS. Model outputs displacement, velocity, or acceleration response histories for each APU component.
- Solutions to assess Influence of APU components on stack response can be performed quickly.
- Frequency response curve for the SOFC stack is generated for use in detailed 3-D model.

Resonant frequencies predicted for the stack.

DOF	Component	Frequency (Hz)
U Z	Separator	188
U Z	PEN	389
U Z	Stack	8907
U X	Stack	3788
U Y	Stack	3788
ROT X	Stack	9472
ROT Y	Stack	9519
ROT Z	Stack	4339

Next Steps

- Include realistic inertial properties for APU components.

Hamilton's Principle

$$\int_{t_1}^{t_2}\delta(T-V)\,dt+\int_{t_1}^{t_2}\delta W_{NC}\,dt=0$$

Potential and Kinetic Energy Expressions for Plate Bending

$$V=\frac{1}{2}\int_0^b\int_0^a D\left[\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)^2-2(1-\nu)\left(\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2}-\left(\frac{\partial^2 w}{\partial x\partial y}\right)^2\right)\right]dxdy$$

$$T=\frac{1}{2}\int_0^b\int_0^a \rho h(\dot{w})^2\,dxdy \qquad \text{where } D=\frac{Eh^3}{12(1-\nu^2)}$$

Equation of Motion for SDOF Representation of Plate

$$m^*\ddot{Z}(t)+c^*\dot{Z}(t)+k^*Z(t)=0$$

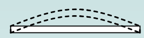
Generalized Parameter Expressions (undamped)

$$m^*=\int_A \rho h\Psi^2(x,y)\,dA$$

$$k^*=\int_A D\left[\left(\frac{\partial^2\Psi}{\partial x^2}+\frac{\partial^2\Psi}{\partial y^2}\right)^2-2(1-\nu)\left(\frac{\partial^2\Psi}{\partial x^2}\frac{\partial^2\Psi}{\partial y^2}-\left(\frac{\partial^2\Psi}{\partial x\partial y}\right)^2\right)\right]dA$$

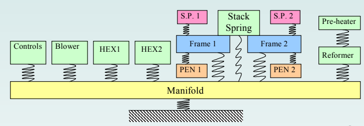
Assumed Mode Shape for Simply Supported Plate

$$\Psi(x,y)=\sin\left(\frac{\pi x}{a}\right)\sin\left(\frac{\pi y}{b}\right)$$

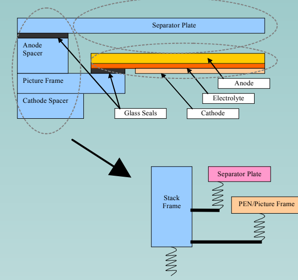


Generalized Parameters

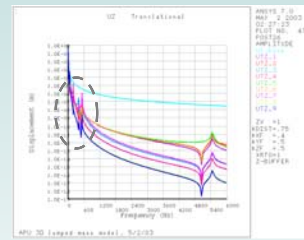
$$m^*=\rho h\frac{ab}{4} \qquad k^*=\left(\frac{Eh^3}{12(1-\upsilon^2)}\right)\left(\frac{\pi^4}{4ab}\right)\left(\frac{b^2}{a}+\frac{a^2}{b}\right)^2$$



Lumped parameter representation of APU model components



The cell is modeled as three masses representing the stiff outer frame, the separator plate, and the PEN/picture frame.



Resonant stack frequencies observed near 200-400 Hz.

3-D Finite Element Model

Detailed model to analyze dynamic stresses in the stack materials.

Approach

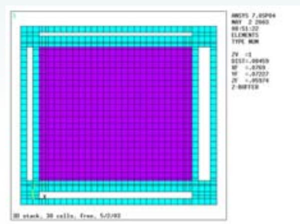
- Obtain spectrum response solution for full 3-D model of 30 cell SOFC stack based on response curve from lumped parameter model.
- Determine dynamic stresses in the stack materials, particularly for the PEN structure and glass seal interfaces.

Results

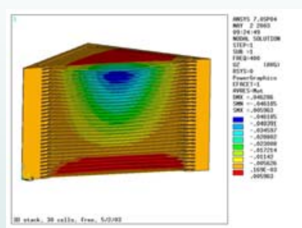
- Generic stack model generated in ANSYS. Model currently performs a modal solution to identify critical frequencies and a harmonic solution to obtain stresses at a given frequency.
- Dynamic stresses obtained for the PEN materials and glass seals. The model also includes contribution of thermal stresses due to temperature distribution and CTE mismatches.

Next Steps

- Extend solution method to perform spectrum response.
- Perform parametric analysis to identify sensitivity of stresses to various stack parameters.

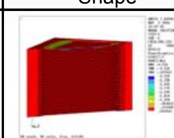
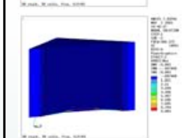
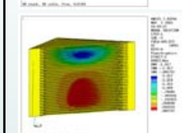
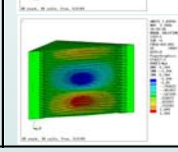


Footprint for generic stack (0.155 x 0.145 m)



Displaced geometry for 4 g translation loading at 400 Hz

Modal results for 30 cell stack

Frequency (Hz)	Mode Shape
285 (Separator Plate)	
366 (PEN)	
409	
410	

Component Failure Modeling

Incorporate failure models into the detailed FEA model to determine vibrational limits for the stack.

Approach

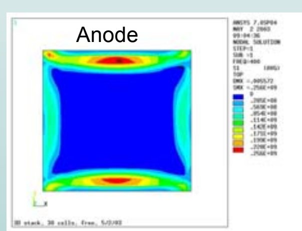
- Leverage existing DOE-funded failure modeling for SOFC materials.
- Incorporate fracture and thermal shock criteria into the FEA model.
- Identify vibrational limits for the APU based on component stresses and failure criteria.

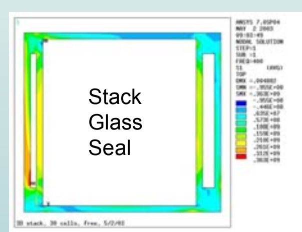
Results

- High localized stresses observed in the PEN and seals indicate that failure modeling is required for moderate acceleration loads.

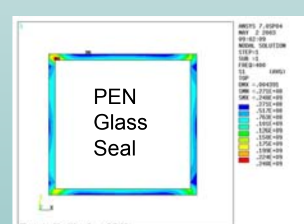
Next Steps

- Collaborate with Georgia Tech student to incorporate their SOFC failure models.





Principal stresses in the glass seals and PEN materials due to 4 g translational loading exhibit localized stresses in excess of estimated fracture strengths. (YSZ ≈ 100-300 MPa, Ni/YSZ ≈ 100 MPa, glass ≈ 50-100 MPa)



Solid Oxide Fuel Cell (SOFC) Modeling

Represent electro-chemical and thermal behavior of an SOFC.

Approach

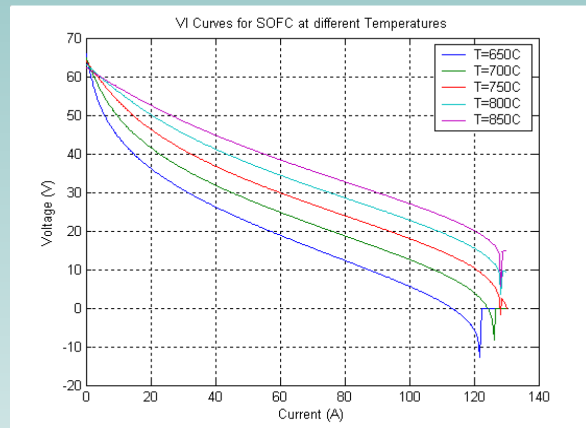
- Leveraging off existing DOE funded electro-chemical models of SOFCs, converting to MATLAB for use in controller development.
- Extending static models to include dynamics, focusing on thermal portion of the SOFC stack.

Results

- SOFC model implemented in MATLAB. Model outputs anode and cathode exhaust compositions and temperatures, fuel utilization, cell voltage and waste heat.
- Model predicts changes in stack temperature during heat-up and operation phases. Stack temperature affects electro-chemistry.
- Model captures important dynamics, showing effects of changing temperatures and behavior during heat-up phase.

Next Steps

- Improve thermal model during operation phase, incorporating results from CFD modeling efforts.



VI Curves for SOFC generated from MATLAB model show the dependence of fuel cell performance on stack temperature.

Auxiliary Power Unit (APU) System Model

The APU System model comprises the SOFC, reformer and support components that make up the APU, as well as the controller, power conditioning electronics and electrical hotel loads powered by the fuel cell.

Approach

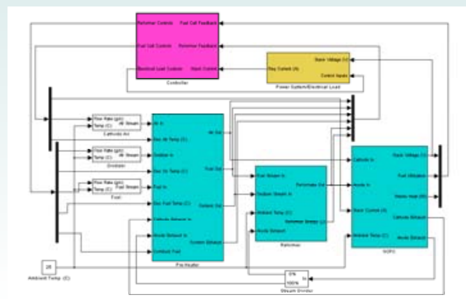
- Create modular models to allow investigation of different connectivity options and allow for continual improvements.
- Use diesel POX reforming for applicability to trucks.
- Model power system to convert SOFC voltage to fixed bus voltage. Focus electrical load models on a few major loads such as HVAC.

Results

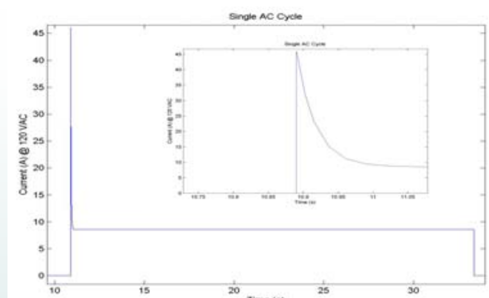
- Complete system model created in MATLAB.
- Model of HVAC based on commercial unit. Inrush current when AC turned on is included. Model uses physical dimensions of an actual truck and includes a 100W occupant heat source.

Next Steps

- Complete implementation of diesel based POX reformer.
- Incorporate latest power electronic modeling work.



MATLAB model of APU System including controller and electrical system/load.



Single Air Conditioner cycle (insert showing detail of inrush current).

Controls

The APU system is a challenging multi-input, multi-output (MIMO) control problem. The controller needs to make sure that the APU is operating at a point that can satisfy the electrical load requirements at all times, while minimizing fuel use. Long heat-up times for the SOFC mean that the controller must anticipate load requirements.

Approach

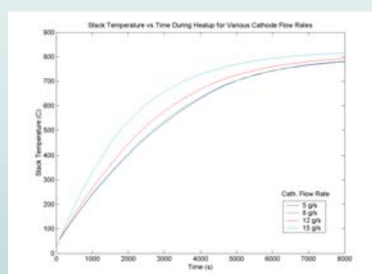
- Design separate controllers for heat-up and operating phases.
- Controller predicts load requirements based on prior usage.
- Build system identifiers to infer internal, distributed parameters of the SOFC stack. Knowledge of these variables can improve system performance and increase stack lifetime.

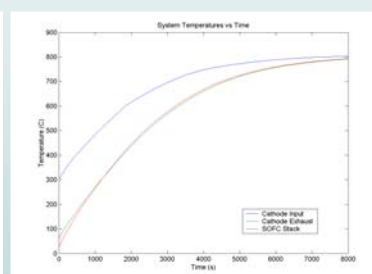
Results

- Completed controller for heat-up phase. Controls cathode air temperature based on stack temperature to prevent thermal shock and fatigue in SOFC stack.

Next Steps

- Implement operating phase controller.





Control Variables

Diesel flow rate

POX air flow rate and temperature

Reformate temperature

Cathode air flow rate and temperature

Anode re-circulation percentage

Stack current

System Outputs

Stack Voltage

Fuel Utilization

Anode and cathode exhaust

Stack Temperature